Fermi National Accelerator Laboratory

Passive Correction of Persistent Current Multipoles in Superconducting Accelerator Dipoles[*]

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PASSIVE CORRECTION OF PERSISTENT CURRENT MULTIPOLES IN SUPERCONDUCTING ACCELERATOR DIPOLES*

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Abstract. - Correction of the magnetization
sextupole and decapole fields with strips of
superconductor placed just inside the coil winding
is discussed. Calculations have been carried out
for such a scheme, and tests have been conducted
on a 4 cm aperture magnet. The calculated
sextupole correction at the injection excitation
of 330 A, 5% of full field, was expected to be 77%
effective, while the measured correction is 83%,
thus suggesting the scheme may be useful for
future accelerators such as SSC and LHC.

INTRODUCTION

The persistent currents in superconducting
filaments generate unwanted multipole fields in
accelerator magnets. These fields, typically a
few gauss at the reference radius, present a
challenge to the accelerator builder since such
fields must be corrected if the accelerator is to
operate over a large range, such as injection at
5% of the top energy. These fields may be
corrected with full length correction coils inside
the dipoles, or it may be possible, with very
small diameter filaments, to correct these
hysteretic fields with correction elements located
at one place in each half cell of the lattice.
Full length correction coils that are driven with
external power supplies or that are shorted and
driven by unwanted flux have been discussed.[1,2]
The device described here is different in that no
power supply is required and no coil of exacting
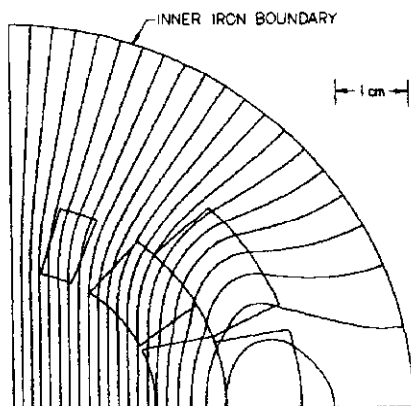dimensions is used.

Figure 1. Sketch of the first quadrant of the
SSC design D 4 cm aperture dipole
cross section showing conductor
blocks and magnetic field lines.

The theory of induced magnetization by
persistent currents is discussed in papers by
C. P. Bean[3] and M. A. Green.[4] The positive and
negative current density induced in a single
filament, due to the flux change caused by ramping
the magnet, creates a source of magnetic dipoles
that persist as long as the magnet is
superconducting. Because of the coil winding
geometry, these persistent current dipoles
generate geometrically allowed macroscopic fields:
dipole, sextupole, decapole, etc. Brown and Fisk
have described a way to harmonically correct the
persistent current fields with longitudinal strips
of superconductor located inside the coil where
harmonically the field is primarily dipole.[5] This
paper describes a test of a 4 cm aperture 1 meter
long SSC design D dipole outfitted with a
corrector that employs 32 strips of approximately
1.2 mm square cross section copper and
superconductor.

PRE-CORRECTION MAGNET TEST

A sketch of the first quadrant of the dipole
winding cross section and its magnetic field are
shown in Figure 1. The two layer coil design has
2 (1) wedges in the inner (outer) layer to improve
field quality. To calculate the persistent
current sextupole the induced magnetization of the
cable must be known as well as the local field
inside the winding. Figure 2 shows cable
magnetization as a function of external magnetic
field[6] for the inner layer design D cable that is
made from 23 strands of .808 mm wire with 23.8 μm
filaments and the outer cable that is made from 30
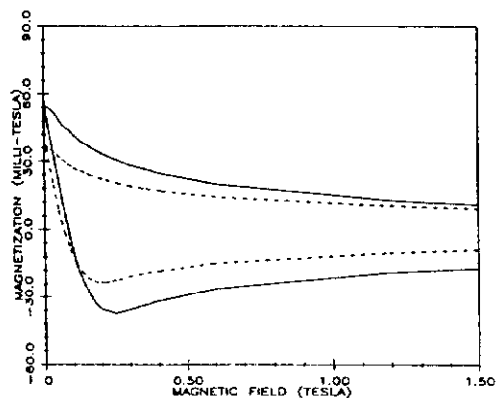strands of .648 mm wire with 16.4μm filaments.

Figure 2. Measured cable magnetization. The
solid (dashed) line refers to cable
used in the inner (outer) layer.

The multipole expansion for the principal component, B_y, of the magnetic field in polar coordinates (r,θ) is

$$B_y = \bar{B} \sum_{n=o}^{\infty} \left(\frac{r}{\rho}\right)^n (b_n \cos n\theta - a_n \sin n\theta)$$

$$b_o = 1.0$$

$$a_o = 0.0$$

where $\bar{B}$ is the magnitude of the dipole field; ρ is the reference radius, here equal to 1 cm; and b_n and a_n are the normal and skew multipole moments, respectively. The pole number is $2n + 2$, i.e., the normal sextupole moment is b_2. It is customary to report b_n and a_n in "units" obtained by suppressing a factor of 10^{-4}. The multipole fields B'_n due to persistent currents can be calculated from an integral over the coil cross section:

$$B'_n = \bar{B}b'_n = \frac{3(n+1)\mu_0}{4\beta} \int \frac{M(B) \cos [(n+2)\theta_c - \alpha] \, dA}{r_c^{n+2}} \; ;$$

where the magnetization $M(B)$ is obtained by direct measurement. Here (r_c, θ_c) are polar coordinates for the point of integration in the winding, $dA = r_c dr_c d\theta_c$, β is the ratio of the total coil area to metal area, and the angle α is the direction of the induced dipoles relative to the main dipole direction. The moments b'_n add to the moments generated by the excitation current to give the total moments b_n.

The theory cited above relates M to other cable properties by

$$M = \frac{4}{3\pi} \frac{\epsilon J_c D}{1 + C/S} \, .$$

Here ϵ is the penetration factor, J_c is the critical current density, and D the filament diameter. The quantity C/S is the area ratio of copper to superconductor. Figure 3 shows the calculated contributions to the sextupole field for inner and outer layers as a function of θ_c at injection, where the central dipole field is about 0.3 T.

Multipole data are obtained from voltage induced in a Morgan coil rotating at 6Hz inside a warm finger located in the cold magnet bore. The voltages are transferred via slip-rings to either a BNL style magnetometer[7] or a lock-in amplifier measuring system. For the magnetometer analysis, square wave gates are generated that can be used to multiply the Morgan coil induced signals which are then sampled and digitized. The measured dipole field is obtained by gating the dipole Morgan coil with a synchronous signal that is positive for the first half cycle of rotation and negative for the second half; i.e. a 6Hz square wave (1θ gate). Sextupole fields are obtained with an 18Hz square wave (3θ gate) applied to the output of the sextupole Morgan coil. Other multipoles such as quadrupole, octupole, decapole, etc. are obtained by using the proper gate/coil
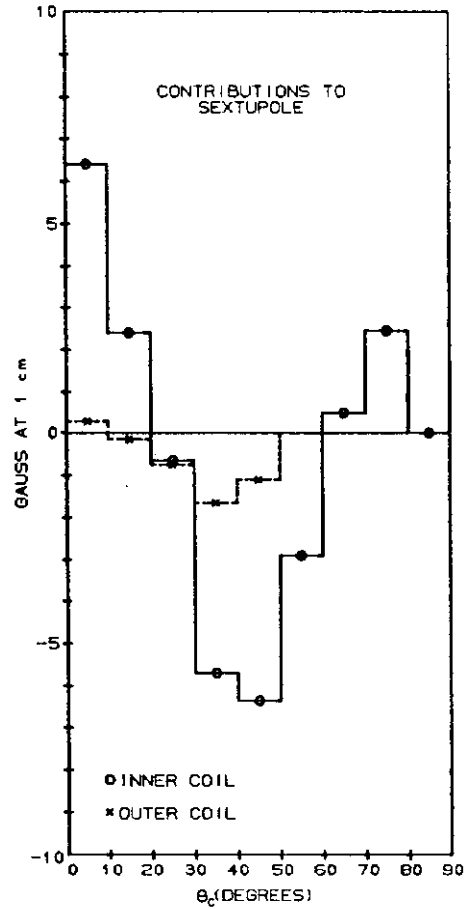

Figure 3. Angular dependence of the persistent current contributions to the sextupole field for both the inner and outer layers of the coil.

combination. Both normal and skew moments can be determined by use of orthogonal square wave (i.e. the sine-like and cosine-like) gates. The lock-in amplifier measuring technique is similar except that the square wave gating signals serve as references to the lock-in. Both measuring systems work well and results that are independently processed agree. The magnetometer is faster in that readout may be obtained as frequently as every 0.5 seconds. For very small signals, especially those that result from low current in the magnet, the lock-in system is more accurate.

Figure 4 shows the normal measured sextupole moment of the magnet without corrector as a function of excitation current and the expected behavior calculated using the magnetization data shown in Figure 2. The data were obtained for two different ramp rates, 2A/s and 12A/s, with the magnetometer system. Although the agreement between the measured data and theory shows some

systematic differences, the agreement at the injection current of 330A is quite good. The only known effect not taken into account is the distortion that transport current may impose on the persistent currents. This effect is expected to be only a few percent at the field levels encountered near injection.

At 330 A the sextupole is 26 units below the value of -21 units due to transport current only. This big persistent current sextupole moment is due to the large diameter of the filaments used in this early SSC model magnet. Smaller filaments, somewhere between 2 and 8μm, are anticipated for the final SSC magnets.
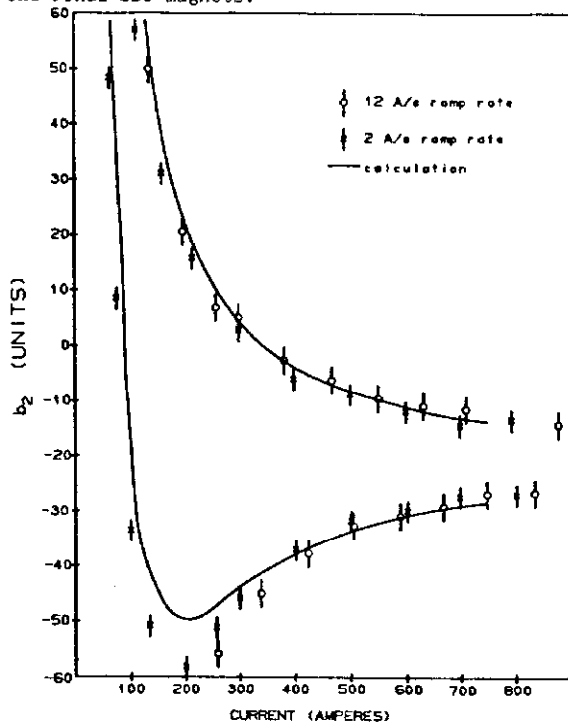

Figure 4. Measured and predicted normal sextupole moment for the uncorrected magnet vs. excitation current. Data were taken with ramp rates of 2A/s and 12A/s.

PASSIVE CORRECTOR

A photograph of the passive corrector is shown in Figure 5 along with the magnet cross section. The 4θ placement of the passive strips is designed to correct the sextupole moment b_2 at low fields without biasing b_2 at high field. Rectangular wire with 45μm filaments was readily available for use in the passive corrector. If time and cost were not factors, the ideal choice of corrector filament diameter would probably fall in the 30μm region since the full penetration of filaments occurs over a smaller range of excitation current. More plainly, the corrector would be more effective at lower magnet excitation.
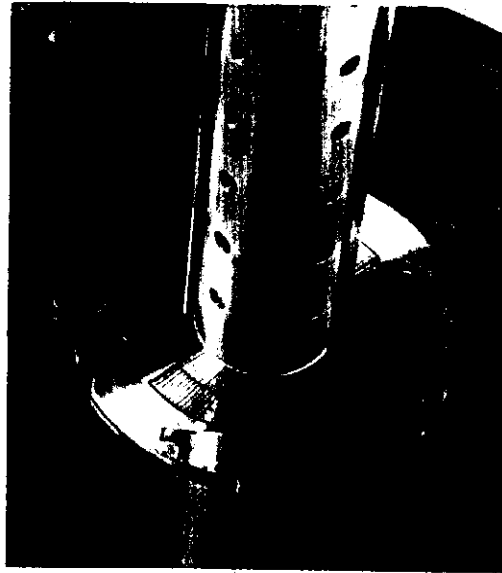

Figure 5. Photograph of the passive corrector and the design D coil cross section.

The corrector, diagramatically shown in Figure 6, was made by machining 32 grooves in an aluminum pipe of inner and outer diameters 1.375" and 1.555", respectively. The grooves were .054" wide by .051" deep such that the rectangular wires could be pressed into them. The strips of passive corrector occupy the region ±22.50° about the x and y axes. The corrector wires are closely packed leaving about 0.022" of aluminum between each strip. There is no insulation on the superconducting wire and the aluminum pipe is perforated with holes to allow liquid He to freely circulate. The aluminum tube with corrector wire is azimuthally positioned by use of guide keys that fit into machined grooves at the top and bottom of the corrector. There are mating guide slots in the stainless steel collar poles that engage the guide keys. The corrector assembly is estimated to be positioned correctly in angle to about ±7mr.

The dimensions of the aluminum tube were chosen to allow the insertion of the multipole measuring apparatus including its warm finger. The aluminum tube itself was not intended to simulate the accelerator beam tube, but was merely a convenient choice from the machining point of view.

The corrector outside diameter is nominally 0.010" smaller than the inside diameter of the coil. This space is filled with kapton insulation wrapped around the corrector. After the 1 m magnet DA1002 had its field measured without correction the corrector was inserted. This turned out to be a fairly elaborate procedure because the magnet was wound on the expanding mandrel at Fermilab and collared without using epoxy. Insertion of the corrector required the collars to be unclamped and in the process the

placement of the conductors in the winding changed enough to give a slightly different transport current sextupole moment.

TEST RESULTS AND PREDICTIONS

Figure 7 shows the sextupole moment of DA1002 with the corrector installed as a function of current for three different ramp rates: 12A/s, 6A/s, and dc. Here dc means the excitation current was held constant long enough for the lock-in system to report a stable signal, typically 30 seconds. The data show a demonstrated ramp rate dependence for the sextupole field. This may be due to eddy currents induced in the aluminum pipe that supports the corrector strips. The proposed SSC ramp rate is 6A/s so that data may be compared directly to the dc data to estimate what improvement would be gained with no ramp rate effects.
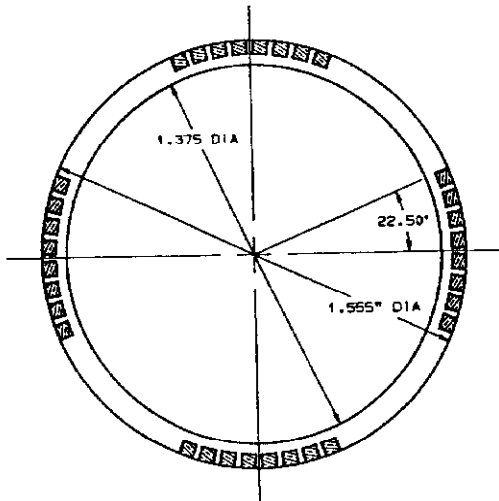

Figure 6. Diagram of the locations of the passive corrector strips as press fitted to the aluminum pipe.

The measured sextupole moment for the dc case and two predictions are shown in Figure 8 along with the uncorrected magnet data. Both predictions use the magnetization for the corrector strips that is shown in Figure 9.[6] In Figure 8 the curve labeled (a) uses the measured hysteresis sextupole field for the magnet alone plus the predicted corrector sextupole field while curve (b) results from adding the calculated sextupole for both the magnet coil and the corrector. Curve (a) is expected to agree with the data better than (b) since less prediction is required. This seems to be the case although there is again a systematic difference between the prediction and observation. If one assumes curves (a) or (b) the anticipated reduction in the sextupole moment at 330 A is in the range 67% to 77%. The measured result is a reduction of 83%. Although a slightly better result could be obtained with a different passive conductor arrangement, this is already a big improvement over the uncompensated field and adequately demonstrates the passive corrector principle.
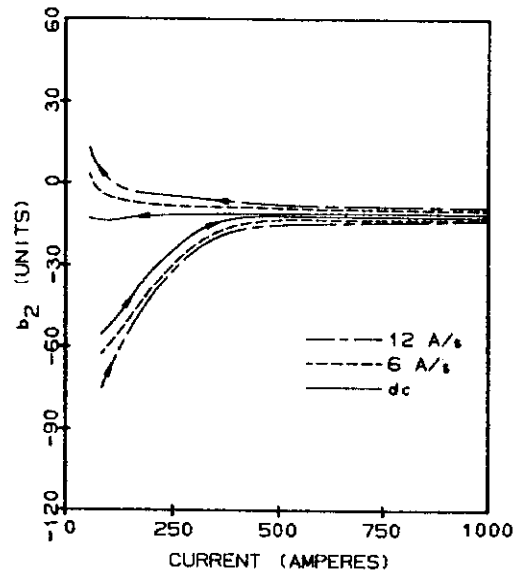

Figure 7. Measured sextupole moment for the passively corrected dipole DA1002. Three sets of data are shown: 12A/s, 6A/s and dc.
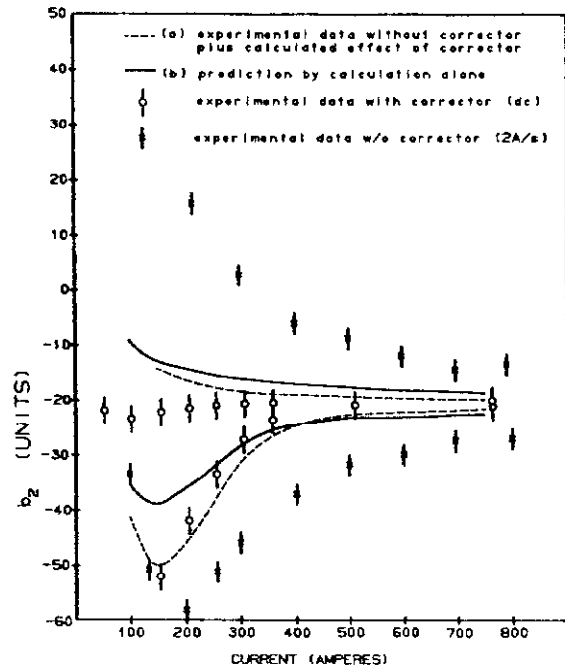

Figure 8. Comparison of the measured and predicted sextupole field. See the text for an explanation of the predictions.

Although it is possible to build a corrector that is effective in simultaneously correcting both sextupole and decapole hysteresis, the corrector described here is expected to have no effect on the decapole, and within errors the measurements so confirm.

COST

The monetary cost of making a correction this way is of interest. For the example discussed here the NbTi in the magnet cross section is 148 mm² per quadrant while the passive corrector's NbTi is 6.1 mm². Thus, the corrector superconductor cost is about 4.1% of the magnet superconductor. Given that the conductor for the dipoles will cost $300M the corrector superconductor cost would be in the neighborhood of $12 to $15M if the area ratios could be kept to the 4 to 5% range. The cost of attaching the passive corrector to the beam tube is probably not more expensive than the cost of attaching the present multiwires and the placement is probably not as critical. There would also be cost savings relative to power supplies, cables, control circuitry and driving software.
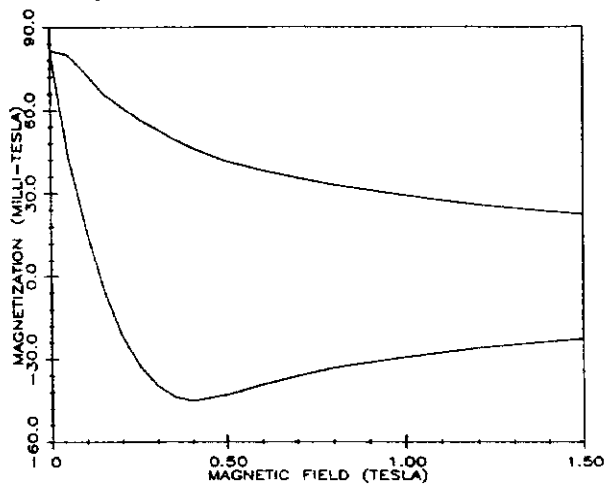

Figure 9. Measured magnetization for the rectangular cross section wire used in the passive corrector.

DISCUSSION

If the field quality needed at injection can be obtained with this passive corrector there are a number of advantages over full length driven correction coils:

(1) automatic temperature compensation;
(2) elimination of power supplies, cables, electronics, etc.;
(3) no incorrect polarities (the fields can be reset by going through a $\Delta I = 500$ A hysteresis loop);
(4) there is no transport current in the corrector so that in the event of a magnet quench the corrector cannot burn up;

(5) machine operators can't get confused – or at least they can't forget to turn on/off or send wrong current settings to the corrector;
(6) the decapole field can be corrected simultaneously with the sextupole field (additional superconductor would be needed);
(7) cost might be reduced significantly.

There are also some disadvantages:

(1) no tuning is possible;
(2) lumped correctors are still required;
(3) there will be slightly higher superconductor hysteresis losses (a few percent);
(4) a slightly greater amount of radial space may be required for the corrector wire arrangement.

FUTURE PROGRAM

There are still a few tests to do with the present model, DA1002 and its compensator. The temperature independence must be checked and ramp rate dependence needs further investigation. If a new magnet is available a similar corrector could be fabricated on a different support pipe, e.g. G-10 or stainless steel.

When there is new small filament conductor available there will need to be new calculations and new rectangular wire with proper filament diameter will need to be procured. This future test should include an attempt to null the decapole as well as the sextupole.

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[6] A. K. Ghosh, Brookhaven National Laboratory has graciously supplied all the measured magnetization data discussed in this paper. See A. K. Ghosh and W. B. Sampson, Advance in Cryogenic Engineering 32, paper DZ-7 (1986).

[7] C. H. Holbrow, Isabelle Project Technical Note 170, Brookhaven National Laboratory (1979).